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SUMMARY

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An investigation has been conducted to determine the effects of controlled roughness (spheres) on boundary-layer transition for unswept, blunted plates at a free-stream Mach number of 6. The location of boundary-layer transition was determined by heating-rate distributions downstream of the roughness element on the center line of the plates. Experimental data are presented for leading-edge bluntnesses of 0.125 and 0.375 inch (0.318 and 0.953 cm). Tests were made for an angle of attack of 0° and for a test unit Reynolds number per foot (per 30.5 cm) between 1.2×10^6 and 9.2×10^6 .

Blunting the leading edge of a plate has been found to affect the roughness height required to trip the boundary layer by changing the distance that transition must be moved (i.e., the natural transition location). The definition of an effective roughness height for which the end of transition is an arbitrarily chosen constant distance downstream of the roughness location has been utilized in the analysis of the experimental data. With this definition of effective roughness height, it has been shown that blunting the leading edge of a plate reduces the required effective roughness Reynolds number. However, the required ratio of effective roughness height to boundary-layer thickness at the roughness location is essentially constant for both sharp- and blunt-leading-edge plates. The required value of effective roughness height has been shown to decrease with increasing unit Reynolds number for blunt-leading-edge plates. This parameter was found to be essentially constant with varying unit Reynolds number for sharp-leading-edge plates.

Correlation of data for both sharp- and blunt-leading-edge plates by the method of Potter and Whitfield was successful. An evaluation of the application of this correlation technique has been discussed.

Author

INTRODUCTION

The determination of the location of boundary-layer transition in the high supersonic and hypersonic Mach number range is complicated by the effects of possible surface discontinuities. These discontinuities may result from fabricational processes (for

example, rivet heads), from buckling of the skin material, or from ablation of protective heat shields. One technique of studying the results of surface discontinuities on transition location is that of determining the effects of surface roughness. Investigations of the effects of surface roughness on boundary-layer transition may be found in the literature. (See refs. 1 to 21.) The studies in references 2 to 21 were, however, primarily concerned with relatively sharp leading-edge models at Mach numbers below 5. Reference 1 is an investigation of the effects of controlled three-dimensional surface roughness on boundary-layer transition and heat transfer on a relatively sharp leading-edge (leading-edge thickness < 0.004 inch (0.010 cm)) flat-plate model at Mach numbers 4.8 and 6.0.

Because the previous data available in the literature are primarily concerned with sharp-leading-edge models, the purpose of the present report is to extend the work of reference 1 to include the effects of surface roughness on boundary-layer transition on unswept flat plates with blunt leading edges. Current design trends of winged reentry vehicles indicate that the leading edges of the wings must be blunted significantly because of heating considerations. This investigation has two functions: First, to increase knowledge of the effects of surface roughness on boundary-layer transition for models with significant degrees of leading-edge bluntness; and second, to serve as a guide for future high-speed experiments in which it is desired to trip the boundary layer with the minimum size roughness necessary to move the turbulent flow near the roughness elements.

The correlation techniques available in the literature vary considerably as to the definition and determination of the most important parameter in assessing the effectiveness of surface roughness as a boundary-layer trip. Several correlation techniques are applied or discussed for both the present data obtained with blunt-leading-edge models and for the data of reference 1 obtained with sharp-leading-edge models at a free-stream Mach number of 6.

A comparison of the experimental heat-transfer data with theoretical predictions has been made for laminar flow over blunt-leading-edge plates without roughness. Also, the turbulent heat-transfer data for the plates with roughness have been compared with the theoretical predictions by assuming the virtual origin of turbulent flow to be located at the roughness elements.

The experimental investigation was conducted in a variable-density Mach 6.2 blow-down jet at the Langley Research Center for a range of free-stream unit Reynolds number per foot (per 30.5 cm) of approximately 1.2×10^6 to 9.2×10^6 . The two models tested were unswept flat plates with two degrees of leading-edge bluntness. The models were instrumented with thermocouples so that the transition location could be determined from the local-heating-rate results.

SYMBOLS

Measurements for this investigation were taken in the U.S. Customary System of Units. Equivalent values are indicated herein in the International System (SI). Factors relating the two systems are given in reference 22.

b	thickness of cylindrical leading edge indicating amount of bluntness
c_p	specific heat
c_w	specific heat of wall material
d	diameter of roughness elements
h	heat-transfer coefficient
k	vertical height of roughness above plate
M	Mach number
N_{St}	Stanton number
p	pressure
\dot{q}	experimental heating rate
$R_{k,k}$	Reynolds number based on fluid conditions at top of roughness elements and height of roughness, $\frac{\rho_k u_k k}{\mu_k}$
$R'_{k,k}$	correlation parameter (see eq. (5) or ref. 10)
R_o	unit Reynolds number per foot (per 30.5 cm) at outer edge of boundary layer, $\frac{\rho_o u_o}{\mu_o}$
R_{o,x^*}	local free-stream Reynolds number based on distance from roughness location, $\frac{\rho_o u_o x^*}{\mu_o}$

R_{∞}	unit free-stream Reynolds number per foot (per 30.5 cm), $\frac{\rho_{\infty} u_{\infty}}{\mu_{\infty}}$
s	lateral spacing of roughness
T	temperature
t	time
u	velocity component of flow parallel to surface of plate
x	longitudinal distance from leading edge
x_k	distance from leading edge to roughness location
x_t	distance from leading edge to end of transition for model with roughness
$x_{t,o}$	distance from leading edge to end of natural transition
x^*	distance from roughness location
γ	ratio of specific heats
δ	calculated undisturbed boundary-layer thickness at roughness location based on velocity
ϵ	correlation parameter (see eq. (6))
η_r	recovery factor
θ_w	local wall thickness
μ	viscosity
ξ	correlation parameter (see eq. (6))
ρ	density
ω	exponent in viscosity-temperature relation

Subscripts:

aw	adiabatic wall
cr	critical
eff	effective
k	conditions at top of roughness elements
o	local conditions at outer edge of boundary layer
p	laminar plateau
r	recovery
v	distance from virtual origin
w	wall
x_k	distance from leading edge to roughness location
x_t	distance from leading edge to end of natural transition
∞	free-stream conditions

APPARATUS, TEST METHODS, AND DATA REDUCTION

Wind Tunnel

The test program was conducted in a variable-density Mach 6.2 blowdown jet at the Langley Research Center. The tunnel is of the intermittent type exhausting to a 40,000-cubic-foot (1130-m³) sphere which can be pumped to pressures as low as 1 millimeter of mercury absolute. The tunnel has a rectangular test section of 12 inches (30.5 cm) in width and 14 inches (35.6 cm) in height. The model was tested in a position approximately at the center line of the tunnel. Tests were run with tunnel stagnation pressures of approximately 65, 165, 265, 365, 515, and 615 pounds per square inch

absolute (448, 1137, 1827, 2516, 3550, and 4240 kN/m²) with an approximate stagnation-temperature range of 860° to 1020° R (480° to 565° K). The resulting free-stream unit Reynolds numbers per foot (per 30.5 cm) are approximately 1.2×10^6 , 2.7×10^6 , 4.1×10^6 , 5.6×10^6 , 7.7×10^6 , and 9.2×10^6 , respectively. A more detailed description of the tunnel is given in reference 23.

Models

The models tested were flat plates constructed from stainless steel with two degrees of leading-edge bluntness (see fig. 1). For convenience, the leading-edge pieces are referred to herein as leading edge A and leading edge B. Leading edge A was 0.375 inch (0.953 cm) in diameter and leading edge B, which consisted of a 14.5° wedge that tapered to a near hemicylinder, was 0.125 inch (0.318 cm) in diameter. The model assembly was 7.5 inches (19.05 cm) wide and 10.4 inches (26.42 cm) long. As is shown in figure 1(a), the roughness elements (which were mounted on interchangeable roughness strips) were aligned equidistantly from the leading edge ($x_k = 2.87$ inches (7.29 cm)). The spheres were glued into small spherical indentations in the roughness strips. The spacing (s), height above the plate (k), and diameter (d) of the spheres are also given in figure 1.

The instrumentation was located along the center line of the rear plate. A roughness element of each roughness strip was located on the center line so that the instrumentation lay directly in the wake of a roughness element. Two models of the instrumented plate were constructed - one being instrumented with 0.050-inch (0.127-cm) pressure orifices and the other with 30-gage iron-constantan thermocouples. The under-surface of the plate instrumented with thermocouples was slotted along the center line to a width of 0.6 inch (1.52 cm) and a surface skin thickness of approximately 0.020 inch (0.051 cm).

Test Methods and Data Reduction

Pressure tests. - Pressure distributions along the center line of the models were obtained for the smooth plate, for use in the reduction of the heat-transfer data. The local static pressures on the plates were measured by connecting the orifices to pressure transducers. The changes in the electrical signals from the transducers were recorded on a digital-readout recorder. The range of the transducers was 0 to 1 pound per square inch absolute (0 to 6.9 kN/m²). All pressure tests were run on the same support system as was used for the heat-transfer tests.

The pressure data are presented in figure 2. During the pressure tests, mechanical failure of the tunnel prevented testing of leading edge B above $R_\infty \approx 4.1 \times 10^6$. However, tests in the Langley 20-inch hypersonic tunnel (Mach 6) have indicated that variation of

Reynolds numbers R_∞ of 4.1×10^6 to 8.5×10^6 has negligible effects on the pressure distribution for leading edge B. Also, comparisons of the data for $R_\infty \approx 4.1 \times 10^6$ and $R_\infty \approx 7.7 \times 10^6$ for plates with the more blunt leading edge (leading edge A) have indicated very little variation in the pressure distribution. Therefore, the data obtained for leading edge B at $R_\infty \approx 4.1 \times 10^6$ were utilized in the reduction of heat-transfer results at higher Reynolds numbers. For the same reason, the data obtained for leading edge A at $R_\infty \approx 7.7 \times 10^6$ were used in the reduction of heat-transfer data at $R_\infty \approx 9.2 \times 10^6$.

Heat-transfer tests.- The aerodynamic heating was determined by the transient calorimetry technique by which the rate of heat storage in the model skin is measured. The models, originally at room temperature or slightly cooler, were suddenly exposed to the established hypersonic airflow by quick injection from a sheltered position beyond the tunnel wall. Injection was accomplished in less than 0.25 second and the model remained in the tunnel for a maximum of 4 seconds.

The electrical outputs from the thermocouples were recorded on a high-speed digital readout recorder. The reading from each thermocouple was recorded at 0.025-second intervals, converted to a binary digital system, and recorded on magnetic tape. The temperature-time data were fitted to a second-degree curve by the method of least squares, and the time derivative of temperature was computed on a card-programmed computer.

The tunnel-stagnation-temperature range was 860° to 1020° R (480° to 565° K) and the wall temperature of the plate was approximately 550° R (305° K). Because of the short time required for the injection of the model, the plates were considered to have been subjected to a step function in the applied heat-transfer coefficient. The thin-skin equation used to calculate the local surface heating rate (neglecting conduction) was

$$\dot{q} = c_w \rho_w \theta_w \frac{dT_w}{dt} \quad (1)$$

The local heat-transfer coefficient was then calculated by the relation

$$h = \frac{\dot{q}}{T_r - T_w} \quad (2)$$

where T_r is the calculated recovery temperature defined as

$$T_r = T_o \left[1 + M_o^2 \frac{\eta_r (\gamma - 1)}{2} \right] \quad (3)$$

T_w is the measured wall temperature, and M_o is the local Mach number outside the boundary layer calculated from the measured pressure distribution assuming a

normal-shock pressure loss. This method was considered adequate since the measured heat-transfer coefficient is rather insensitive to small errors in M_O . Roughness was considered to have a negligible effect on the pressure distribution of the instrumented plate. Therefore, in the calculation of M_O for equation (3), the smooth-plate distribution was used for all tests. The recovery temperature was calculated by assuming a recovery factor of 0.830 for a laminar boundary layer and 0.883 for a turbulent boundary layer. The Stanton number, based on free-stream conditions ahead of the model, was calculated by the use of the equation

$$N_{St} = \frac{h}{\rho_{\infty} u_{\infty} c_{p, \infty}} \quad (4)$$

The experimental heat-transfer parameters \dot{q} , h , and N_{St} presented in this report were determined by calculating the slope of the temperature-time curve approximately 0.20 second after the model was in position in the tunnel. The nearly isothermal conditions of the tests kept the lateral conduction to a minimum.

Determination of transition.- The method used herein to determine the location of boundary-layer transition from laminar to turbulent flow is the same as that previously described in reference 1. That is, the location of the beginning and the ending of transition has been determined by noting a change in the heat-transfer parameters with longitudinal distance as illustrated in figure 3. The local heating rate decreases for laminar flow until transition begins, which causes the heating rates to increase rapidly. When transition ends (beginning of fully developed turbulent flow), the heating rate peaks and begins to decrease with increasing distance from the leading edge. The transition location x_t as used in this report refers to the end of transition (see fig. 3).

REVIEW OF THE LITERATURE

There is a great deal of variance in the literature as to the choice of parameters for the best correlation of the effect of a given roughness condition on boundary-layer transition. Therefore, a review of the often-used techniques from the literature that are employed in the evaluation of roughness effects is presented to lay the proper background for analysis of the present results.

The concept of a critical roughness Reynolds number appears to have been originally based on experimental results presented by Schiller in reference 3. The results indicated that roughness had no effect on the nature of the flow within the boundary layer until the Reynolds number of the element (based on the characteristic height k) reached a definite critical value at which vortices appeared. An increase in roughness Reynolds number

slightly above this critical value, by either increasing the roughness height or by increasing the local unit Reynolds number, should then cause transition to occur at the roughness element itself. A review of published data on the effect of roughness on transition from laminar to turbulent flow has been presented in reference 4. The methods of Braslow, Knox, and Horton presented in references 5 to 7 for determining the distributed roughness have defined the critical roughness Reynolds number as the value at which turbulent "spots" are initiated behind the roughness and at which a small increase in roughness Reynolds number above this value is required to move the fully developed turbulent boundary layer substantially up to the roughness particles. The experimental values of critical roughness Reynolds number based on this definition were found to vary from 250 to 600 for subsonic and supersonic Mach numbers up to 2. This range of values results in a variation of the parameter of the square root of the critical roughness Reynolds number as first used by Schiller of about 16 to 25, which is an essentially invariant magnitude with Mach number change up to $M = 2$.

Other investigations - for example, the work of Fage, with various-shaped two-dimensional trips (ref. 8) - have indicated that the concept of an almost instantaneous shift of the transition location from its undisturbed position to the roughness position is generally erroneous. In the analysis presented in reference 4, Dryden made use of the ratio of roughness height to the displacement thickness of the boundary layer at the roughness location. Reference 9 reported that although this parameter does serve to correlate roughness effects of two-dimensional trips, it is not sufficient to correlate the roughness effects of a single row of spheres (three-dimensional trip).

Smith and Clutter (refs. 13 and 14) have suggested that the roughness Reynolds number based on roughness height and actual disturbed conditions at the top of the roughness element is a useful correlation parameter in evaluating roughness effects. Thus, if the Mach number is greater than 1 at the top of the element, the roughness Reynolds number should be based on conditions behind a shock.

More recently, Potter and Whitfield (refs. 10 to 12) have demonstrated that both the critical roughness Reynolds number as defined in references 5 to 7 and the ratio of roughness height to boundary-layer thickness are inadequate parameters for the correlation of the effects of three-dimensional roughness on boundary-layer transition at high supersonic and hypersonic Mach numbers. Additional evidence of this conclusion was presented in reference 1.

A review of previous studies of the effect of surface roughness led Potter and Whitfield (ref. 10) to present a semiempirical correlation parameter which may be defined by

$$R'_k \approx R_k \frac{M_p}{M_k} \frac{p_p}{p_o} \left(\frac{1.11}{1 + \frac{\gamma - 1}{2} M_k^2} \right)^{0.5+\omega} \quad (5)$$

where the subscript p refers to the laminar separation plateau value in the region of the roughness element, the subscript k refers to the conditions of height k in the undisturbed boundary layer at station x_k , and the subscript o refers to the edge of the boundary layer. The symbol ω represents the exponent in the viscosity-temperature relation. Experimental results were then correlated (ref. 10) by considering the variation of R'_k as a function of

$$\xi = \sqrt{\frac{x_t}{x_{t,o}}} - \sqrt{\frac{x_k}{x_{t,o}}} \frac{R'_k}{\epsilon} \quad (6)$$

where ϵ is a constant which essentially represents the roughness Reynolds number required to move transition forward to the roughness location (i.e., where $x_k = x_t$). Using the correlation parameter R'_k , Potter and Whitfield were able to correlate two-dimensional and three-dimensional roughness effects for both subsonic and supersonic flow.

The analysis presented in reference 16 by Van Driest and Blumer indicates that after a certain roughness height has been reached, increasing the Reynolds number of the flow will result in a rapid forward movement of the transition position until the transition reaches the region of the roughness. At this point, a "knee" in the x_t curve occurs and a further increase in the Reynolds number will cause the transition to slowly approach the roughness location asymptotically. By the definition of an effective roughness height as that required to move transition to the region of the "knee" in the x_t curve, the experimental results were correlated successfully in references 16 and 17.

The application of the correlation technique of Potter and Whitfield and that of Van Driest to the present data will be discussed in more detail in the section of this paper entitled "Results and Discussion."

RESULTS AND DISCUSSION

Effects of Roughness on Boundary-Layer Transition

The predominant variable in producing transition by three-dimensional spherical surface roughness is the height of the roughness elements relative to the local boundary-layer conditions. A discussion of the effects of increasing roughness height on transition

location relative to the effect of free-stream disturbances is given in reference 1. The work of Van Driest and McCauley in reference 17 indicated that lateral spacing of a single row of spheres has little effect on boundary-layer transition provided the spheres are not so close that they act as a two-dimensional trip. Therefore, the effect of sphere spacing has not been considered in this program. Another variable is the free-stream turbulence level which is strongly influenced by the turbulence input from the tunnel walls. It has not been attempted in this report to account for the free-stream turbulence effects on the experimental results. However, all data for the present investigation were obtained in one tunnel under similar test conditions. Also, much of the information from reference 1, which is compared to the present data, was obtained from the same tunnel at similar test conditions.

Figures 4 and 5 present the heating-rate distributions and Stanton number variations for various size roughness elements as a function of distance from the leading edge of the model for leading edges A and B, respectively. The Stanton numbers plotted in figures 4 and 5 were calculated from the experimental data by assuming a laminar recovery factor for the smooth plate. In the reduction of the data for the plate with roughness to Stanton number form, a turbulent recovery factor was assumed. Also shown in the figures are the theoretical laminar and turbulent Stanton number distributions to serve as a guide in determining the effectiveness of a particular roughness trip. The theoretical Stanton number distributions are based on free-stream conditions, that is,

$$N_{St,\infty} = N_{St,0} \frac{\rho_0 u_0 c_{p,0}}{\rho_\infty u_\infty c_{p,\infty}}$$

and were calculated by the Monaghan reference temperature method as reviewed in reference 1. The local Mach number was assumed to be 3.16 (obtained by taking a normal-shock loss in pressure and assuming that the flow had expanded to the conditions of $p_w/p_\infty = 1$). The virtual origin for the turbulent-flow case was assumed to be located at the roughness position as was done in reference 1. The actual unit free-stream Reynolds number, the ratio of roughness height to boundary-layer thickness as determined by the calculated Monaghan velocity profile of reference 24, and the local unit Reynolds number as calculated by the previously mentioned assumptions in obtaining the theoretical distributions are tabulated in these figures for each test.

In an attempt to analyze the present data by the method of reference 16, the distance between the transition location and the roughness location ($x_t - x_k$) was plotted as a function of the free-stream unit Reynolds number per foot (per 30.5 cm) in figure 6(a). Shown in figure 6(b) is the variation of $x_t - x_k$ with roughness height k . As expected, an increase in R_∞ or k resulted in a decrease in the value of $x_t - x_k$ (i.e., a forward movement of transition). However, the data are insufficient to indicate a definite "knee"

in the variation of $x_t - x_k$ with R_∞ for most roughness heights as the roughness location is approached. From figure 6(a), it can be seen that the location of the "knee" (or the effective roughness height as defined in ref. 16) in the $x_t - x_k$ variation with Reynolds number was determined only for the largest size roughness ($k = 0.0091$ foot (0.2774 cm)) for both leading edge A and B and for the second largest roughness ($k = 0.0067$ foot (0.2042 cm)) for leading edge A. (The variation of $x_t - x_k$ with R_∞ has been faired for these three cases in fig. 6(a).) For the remaining combinations of roughness height and leading edge, the Reynolds numbers necessary to obtain the knee in the curve were beyond the maximum capability of the tunnel. The first thermocouple was located at a distance of 0.57 inch (1.448 cm) from the roughness location. More instrumentation in this region would be desirable for accurate determination of the effective roughness height as defined in reference 16. In addition to the geometry differences between the model used in the investigation of reference 16 and the model used in the present investigation, that is, a sharp cone as compared with a blunt-leading-edge flat plate, a further difference exists which may have significant influence on correlation attempts by the method of reference 16. In reference 16, Van Driest and Blumer greatly reduced the influence of free-stream disturbances as a variable by testing far upstream of the natural transition location. The ratio of roughness height to boundary-layer thickness (k/δ) tabulated in figures 4 and 5 for the present results shows that, generally, the roughness extends outside the boundary layer. Thus, the roughness not only affects the boundary layer but also has a very definite effect on local turbulence level in the inviscid-flow region.

Analysis of the results of Van Driest and Blumer suggests that transition cannot occur at the roughness location but instead approaches this position asymptotically. Because of this result and the difficulties of applying other definitions of critical roughness Reynolds number to the present data for blunt-leading-edge models, the present authors have chosen to define an effective roughness height as the one for which $x_t - x_k = 0.10$ foot (3.05 cm). This definition will allow an analysis of the data that is believed to be adequate for most applications. It is doubtful that roughness-height requirements necessary to move the end of transition closer than 0.10 foot (3.05 cm) from the roughness location are desirable from any but a purely theoretical viewpoint.

It should be noted that the utilization of certain dimensionless parameters such as $\frac{x_t - x_k}{x_{t,o} - x_k}$ or $R_{o,x_t} - R_{o,x_k}$ was not practical in the consideration of the present experimental results. In particular, the quantity $x_{t,o}$ in the parameter $\frac{x_t - x_k}{x_{t,o} - x_k}$ was an unknown that could not be determined experimentally with the models available.

Based on the definition $x_t - x_k = 0.10$ foot (3.05 cm), the effective roughness heights may now be determined from figures 4 and 5. For example, from figure 5(a) for leading edge B and for $R_o \approx 1.10 \times 10^6$, the value $k = 0.0054$ foot (0.1646 cm) would be slightly less than effective whereas the value $k = 0.0067$ foot (0.2042 cm) would be slightly greater than effective. The reader should be cautioned that the value of x_t is determined by fairing the heating-rate curves in the manner shown schematically in figure 3. The technique of fairing has been consistent, but a slightly different technique might yield different quantitative values of x_t . The differences, however, would be small and would not affect the qualitative conclusions of this paper.

Figure 6 indicates that the effective roughness height (that is, the height for which $x_t - x_k \leq 0.10$ foot (3.05 cm)) is generally greater for leading edge B than for leading edge A for a given free-stream Reynolds number. Unpublished data obtained in an investigation conducted in the Langley 20-inch hypersonic tunnel (Mach 6) to determine the bluntness effects on natural transition for a 16-inch plate at an angle of attack of 8° (compression) have shown that an increase in bluntness from a near sharp leading-edge condition causes a delay in transition. However, above a certain bluntness, increasing the bluntness further causes the transition Reynolds number based on free-stream conditions to decrease (i.e., a forward movement of x_t). This result has led to the speculation that the larger roughness heights required to move $x_t - x_k$ to 0.10 foot (3.05 cm) for leading edge B, as compared with that required for leading edge A, may be primarily a result of a larger value of $x_{t,o}$ for the less blunt leading edge at a given set of free-stream conditions.

Effective Roughness Correlations

As was mentioned previously, both the roughness Reynolds number and the ratio of roughness height to boundary-layer thickness at the roughness location are often used as correlation parameters for the effects of roughness on boundary-layer transition. For the present investigation and for the results of reference 1, the roughness height is generally greater than the boundary-layer thickness at the roughness location. Therefore, for a given local Mach number, $R_{k,eff}$ and $(k/\delta)_{eff}$ may be considered to vary primarily as follows:

$$\left. \begin{aligned} R_{k,eff} &= f(R_o, k, x_{t,o}) \\ (k/\delta)_{eff} &= f(R_o, k, x_{t,o}, x_k) \end{aligned} \right\} \quad (7)$$

In figure 7, these parameters are plotted as functions of the local unit Reynolds number for both sharp and blunt leading edges. (Note that the term "sharp leading edge"

is used in connection with the data of reference 1 for which $b < 0.004$ inch (0.010 cm.) Analysis of this figure indicates several differences between the results for the models with blunt and sharp leading edges. The trend of $R_{k,eff}$ for blunt-leading-edge models is less sensitive to local Reynolds number change than is the variation of $R_{k,eff}$ for sharp-leading-edge models. This trend might be expected because of the large differences in $x_{t,o}$ between the two types of leading edge. That is, the value of $x_{t,o}$ for the blunt-leading-edge plate is several times greater than the value for the sharp-leading-edge plate. This difference has been established in an experimental investigation (unpublished) of leading edges A and B on a 16-inch plate at a Mach number of 6.0. The results showed that transition did not occur on the plate even at the highest Reynolds number. Based on the $x_{t,o}$ locations for the sharp-leading-edge plate of reference 1, therefore, the values of $x_{t,o}$ for the blunt-leading-edge plates must be at least on the order of three times greater than those values for the sharp-leading-edge plate.

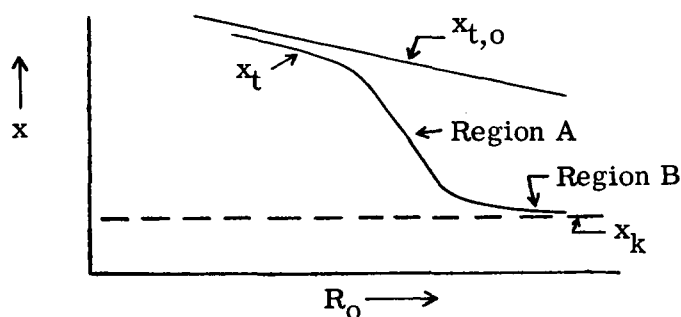
The ratios of the value of $x_{t,o} - x_k$ for the sharp-leading-edge plates to that for the blunt-leading-edge plates are necessarily larger than the ratios of the value of $x_{t,o}$ for the sharp-leading-edge plate to that for the blunt-leading-edge plate, since the x_k locations were generally equal in the two tests. Therefore, for the Reynolds number range under consideration, it seems reasonable that the roughness height would be the more predominant factor in determining $R_{k,eff}$ for the blunt-leading-edge plate. However, as is shown in figure 7(b), for increasing R_o , the value of $(k/\delta)_{eff}$ decreases for the blunt-leading-edge plate. This trend could indicate an increased importance of R_o relative to roughness height in determining effective roughness criterion. From figure 7(b), the values of $(k/\delta)_{eff}$ for both sharp- and blunt-leading-edge models (at $M_\infty = 6$) lie within the range of 1.5 to 3.0. It can be clearly noted from figure 7 that both the required value of $R_{k,eff}$ and of $(k/\delta)_{eff}$ are slightly greater for leading edge B than for leading edge A.

R'_k correlation.- Study of the literature has indicated that the most applicable correlation technique for the present results and those of reference 1 on the effects of roughness on boundary-layer transition is that given by Potter and Whitfield in reference 10. However, application of this correlation to the present data and to the sharp-leading-edge data of reference 1 has demonstrated several points that are of interest. The data are presented in figure 8(a) in terms of the parameter R'_k as suggested for correlation in reference 10. (See eq. (5).) The ratio $\frac{M_p p_p}{M_k p_o}$ in equation (5) was taken

as having a value of 1.0 as was suggested in reference 10. The actual value varies with R_o and is 1.15 ± 0.05 . Both the sharp- and the blunt-leading-edge data correlate on reasonably smooth curves, but neither agree with the correlation curve from reference 10. Differences exist between the data of the present investigation and those upon which the

correlation curve was based. First, the model was not at adiabatic conditions as in reference 10. However, the correlation equations take into account the difference in T_w/T_{aw} conditions; therefore, these differences should not greatly affect the correlation. Second, the relatively large value of $x_{t,o}$ for the blunt-leading-edge model, as compared with the sharp-leading-edge model of reference 1, should not necessarily cause large errors since the $x_{t,o}$ effect is included in the correlation. (Values of $x_{t,o}$ for the blunt-leading-edge model could not be obtained experimentally. For the correlation of data in figure 8, the value of $x_{t,o}$ was obtained by assuming a constant local transition Reynolds number of 3×10^6 . Consideration of several values of $x_{t,o}$ indicated that this parameter affected the correlation of data by slightly varying the shape of the curve but that it had no effect on the indicated value of ϵ . Therefore, a constant transition Reynolds number was considered to be sufficient for the present analysis.) Finally, the local Mach number of 6 for the sharp-leading-edge data is beyond the range $M_o = 1.9$ to 5.0 for which ϵ was defined in reference 10. However, since ϵ was defined as constant for this particular range, it does not seem reasonable to expect the value of ϵ to change drastically at a Mach number of 6.

The following sketch shows the trends of a typical variation in transition location with increasing unit Reynolds number for a smooth plate and a plate with roughness (see ref. 16):



Potter and Whitfield (ref. 10) indicated that the exact value of ϵ used in the correlation is not critical. Although they recognized that ϵ may be somewhat in error, they stated that such an error would affect results in correlation only in the region of this sketch where $x_t \approx x_k$ (region B). Therefore, in the region (region A) where the characteristic "knee" is used to define effective roughness size by the method of Van Driest and Blumer (ref. 16), errors in ϵ would be insignificant in correlating the data according to reference 10.

The present results indicate that an error in ϵ can affect results in an area other than of region B (see sketch). Also, the assumption of a constant value of ϵ of 3000 as was done in reference 10 can lead to an erroneous concept. In figure 8(a), the variation

of R'_k is presented for both positive and negative values of ξ for $\epsilon = 3000$. This figure shows conclusively that the use of $\epsilon = 3000$ results in negative values of the correlation parameter ξ , which would indicate transition prior to the roughness elements. The values of $x_t - x_k$ as a function of ξ are also shown in figure 8(b). The magnitude of these values of $x_t - x_k$ for which $\xi < 0$ would indicate that the data for which ξ is negative are either in region A or to the left of region A. The reader is reminded that the characteristic "knee" in the variation of $x_t - x_k$ with R_0 was not obtained for most of the present data (see fig. 6). Also, from figure 6, it can be seen that the "knee" was not reached for the data from reference 1 (shown as diamond flagged symbols in fig. 8). Therefore, the assumption of $\epsilon = 3000$ would rule out of consideration a substantial amount of data which is definitely not in region B of the preceding sketch if the data for which ξ is negative were eliminated. (It is interesting to note, however, that if the data for which $\xi < 0$ were ignored in figure 8(a), the data for leading edges A and B would indicate a value of ϵ approximately equal to 3000.)

The near asymptotic approach of x_t to the x_k location in region B of the preceding sketch as demonstrated by Van Driest and Blumer (ref. 16) would indicate that R'_k might be expected to increase to very large values as x_t approaches x_k . The concept of an instantaneous beginning of turbulent flow at the roughness location is probably fictitious since transition to turbulent flow should be expected to occur over some finite distance. Therefore, ϵ should be determined by fairing the results to zero for data prior to the occurrence of region B. (Realization of this fact led the present authors to define effective roughness Reynolds number based on an arbitrary distance of $x_t - x_k = 0.10$ foot (3.05 cm).)

From figure 8(a), fairing of the present data and those from reference 1 suggests the use of $\epsilon \approx 5500$. The data are seen to correlate very well in figure 9 based on $\epsilon = 5500$. The errors which can result from the selection of ϵ are relatively insignificant when a correlation of data is desired. However, in the practical application of the correlation method, that is, the estimation of the minimum height of roughness necessary to move transition approximately to the roughness location, it is suggested that the value of R'_k be determined without consideration of a value of ϵ . In applying the correlation of Potter and Whitfield to roughness data, the suggested value of ϵ can be used to reduce the data (for example, $\epsilon = 3000$ for three-dimensional roughness). From the results of the first correlation, a new value of ϵ may be determined which will lead to a more satisfactory final correlation result.

Critical roughness height. - It has been stated previously that a definition of $x_t - x_k = 0.10$ foot (3.05 cm) is considered adequate for determining effective roughness heights for most applications. In figure 10, the effective roughness heights determined from the present data and reference 1 are plotted as a function of free-stream Reynolds

- number. If the critical roughness height is defined as that roughness for which the end of transition is essentially at the roughness element, then the variation of k_{cr} with free-stream Reynolds number can be calculated from the Potter and Whitfield correlation results. The curves representing the variation of k_{cr} with R_∞ are also shown in figure 10 for $M_0 = 3.16$ and $M_0 = 6.0$ ($\epsilon = 5500$). From the figure it can be seen that k_{cr} is much larger than the measured k_{eff} at the lower free-stream Reynolds numbers. For example, when $R_\infty \approx 2.5 \times 10^6$, the value of k_{cr} is approximately three times larger than the value of k_{eff} for a sharp leading edge. This would lead to a value for k_{cr}/δ of the order of 6 to 9. The value of k_{cr} , of course, would be expected to be significantly larger than that of k_{eff} because of the difference in definition of the two parameters.

The trend of k_{eff} for the blunt-leading-edge plates follows approximately that given by the Potter and Whitfield correlation method, but the values are lower as expected. (See fig. 10.) For the sharp-leading-edge plates, however, k_{eff} is essentially constant over the complete Reynolds number range. This result is thought to be primarily caused by the $x_{t,o}$ location for the sharp-leading-edge plates. That is, $x_{t,o}$ is very close to x_k for the sharp-leading-edge test conditions and R_0 is the predominant parameter in the determination of k_{eff} .

The differences in magnitude between k_{eff} and k_{cr} add justification to the utilization of an arbitrary definition of effective roughness height, such as that for which $x_t - x_k = 0.10$ foot (3.05 cm), if minimum flow distortions are to be obtained.

CONCLUSIONS

An investigation has been conducted to determine the effects of controlled surface roughness on boundary-layer transition determined by heating-rate distributions for unswept, blunted plates at a free-stream Mach number of 6. The location of boundary-layer transition was determined by heating-rate distributions downstream of the roughness element on the center line of the plates. Data are presented for a free-stream Reynolds number per foot (per 30.5 cm) between approximately 1.2×10^6 and 9.2×10^6 and for a nominal angle of attack of 0° . Analysis of the experimental results is based on a definition of effective roughness height as being that for which the distance between the end of transition and the roughness location is an arbitrarily chosen constant. These results and a comparison with theory and previous results from the literature have led to the following conclusions:

1. The required value of effective roughness height decreases with increasing unit Reynolds number for blunt-leading-edge plates, but is essentially constant with varying unit Reynolds number for sharp-leading-edge plates.

2. The effective roughness height as defined in this report is considerably smaller than that required to reach conditions for which the end of transition occurs approximately at the roughness element based on a previously derived correlation, particularly at the lower test Reynolds numbers.

3. For a constant free-stream Mach number of 6, blunting the leading edge had only a small effect on the required values of the ratio of effective roughness height to boundary-layer thickness at the roughness location. For both sharp- and blunt-leading-edge plates, the values of this ratio were within the range of 1.5 to 3.0.

4. Blunting the leading edge of the plates resulted in a considerably smaller value of effective roughness Reynolds number than was previously found for a sharp-leading-edge plate at similar test conditions.

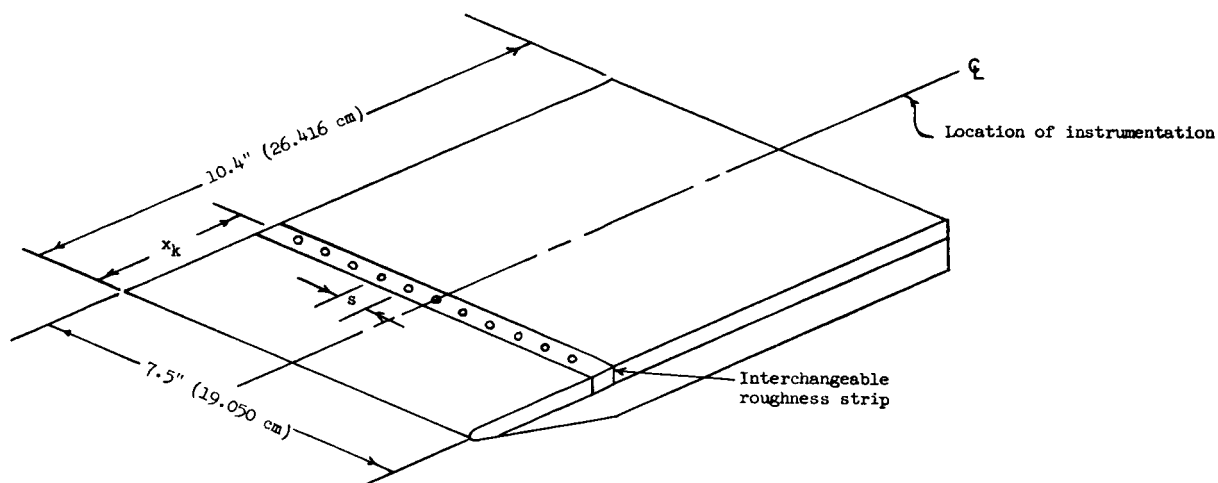
5. It has been shown that the Potter and Whitfield method will correlate roughness-induced-transition data for both sharp- and blunt-leading-edge plates at a free-stream Mach number of 6.0.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 28, 1966.

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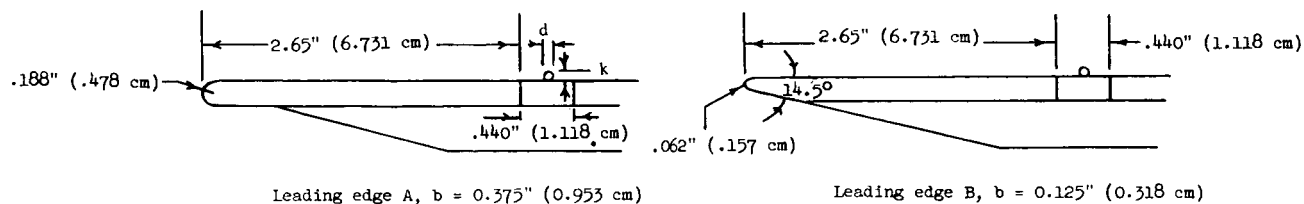
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(a) Flat-plate assembly.

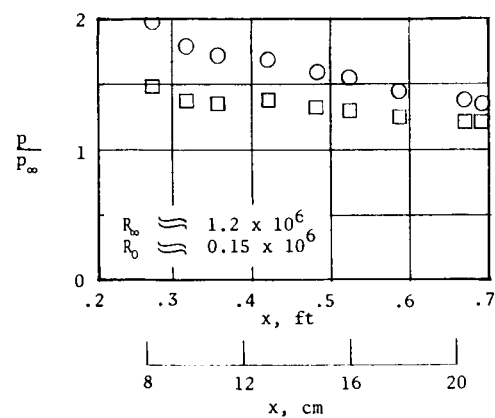
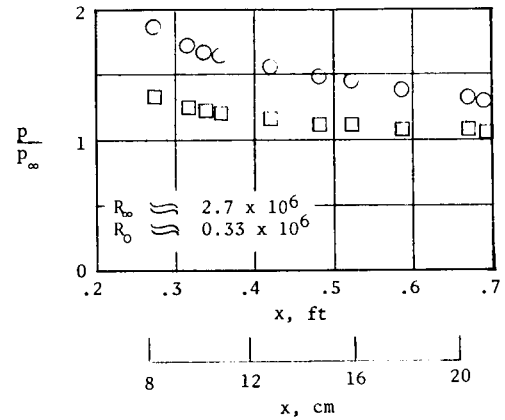
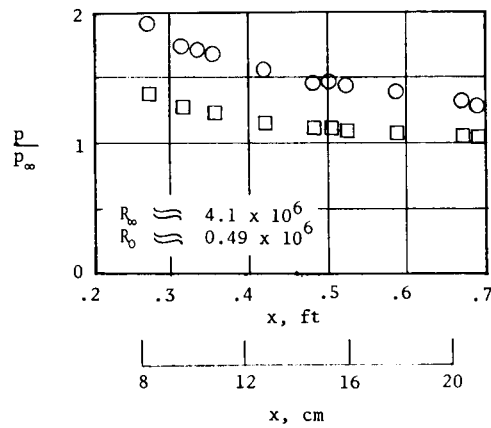
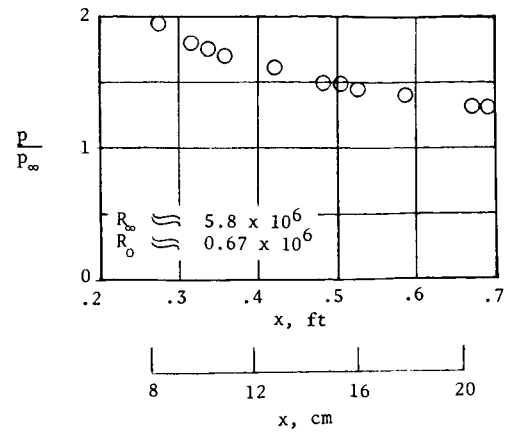
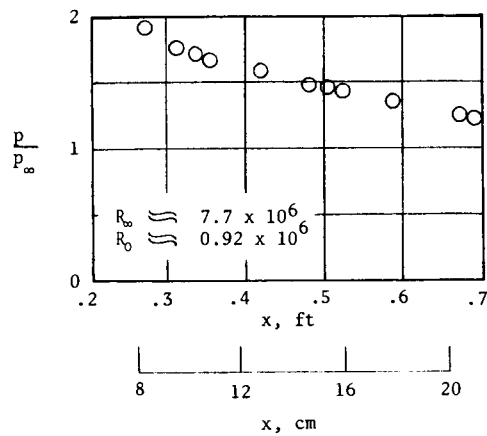
Characteristics of spheres

k		d		s		x_k	
ft	cm	ft	cm	ft	cm	ft	cm
0	0	0	0	0	0	.239	7.290
.0018	.0549	.0026	.0792	.0167	.5090	.239	7.290
.0030	.0914	.0039	.1189	.0167	.5090	.239	7.290
.0044	.1341	.0053	.1615	.0167	.5090	.239	7.290
.0054	.1646	.0065	.1981	.0260	.7925	.239	7.290
.0067	.2042	.0078	.2377	.0260	.7925	.239	7.290
.0091	.2774	.0104	.3170	.0260	.7925	.239	7.290



(b) Leading-edge details.

Figure 1.- Sketch of model.



○ Leading edge A
 □ Leading edge B

Figure 2.- Pressure distributions on flat plate with two degrees of leading-edge bluntness over a range of Reynolds numbers.

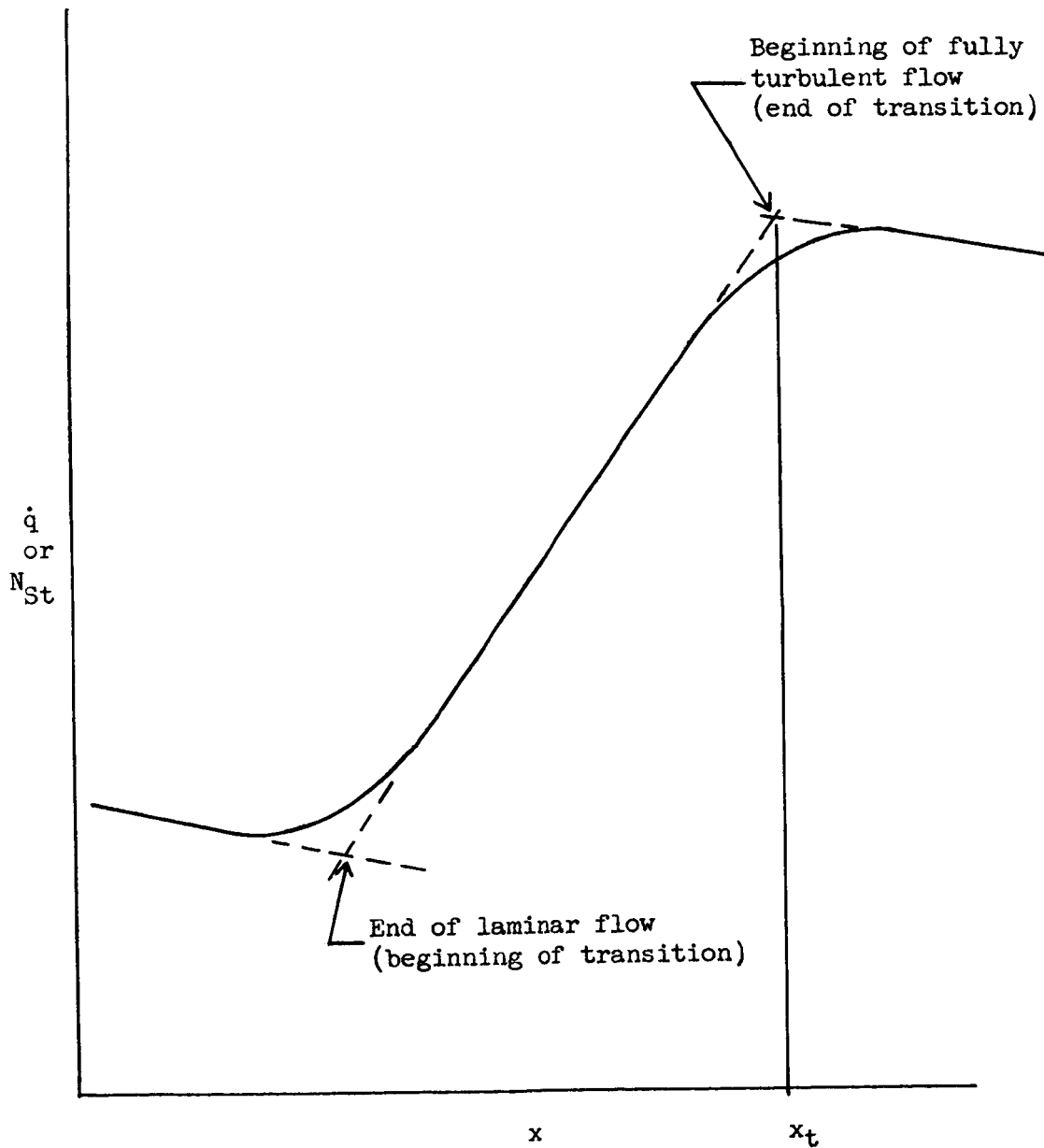
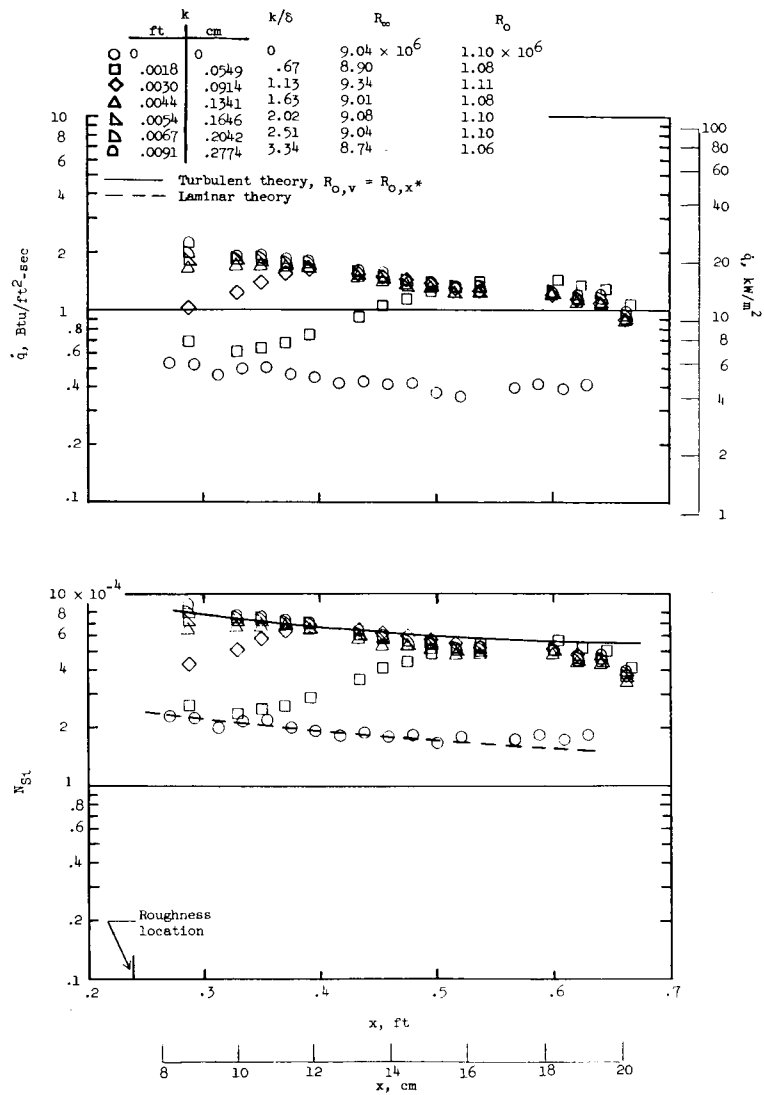
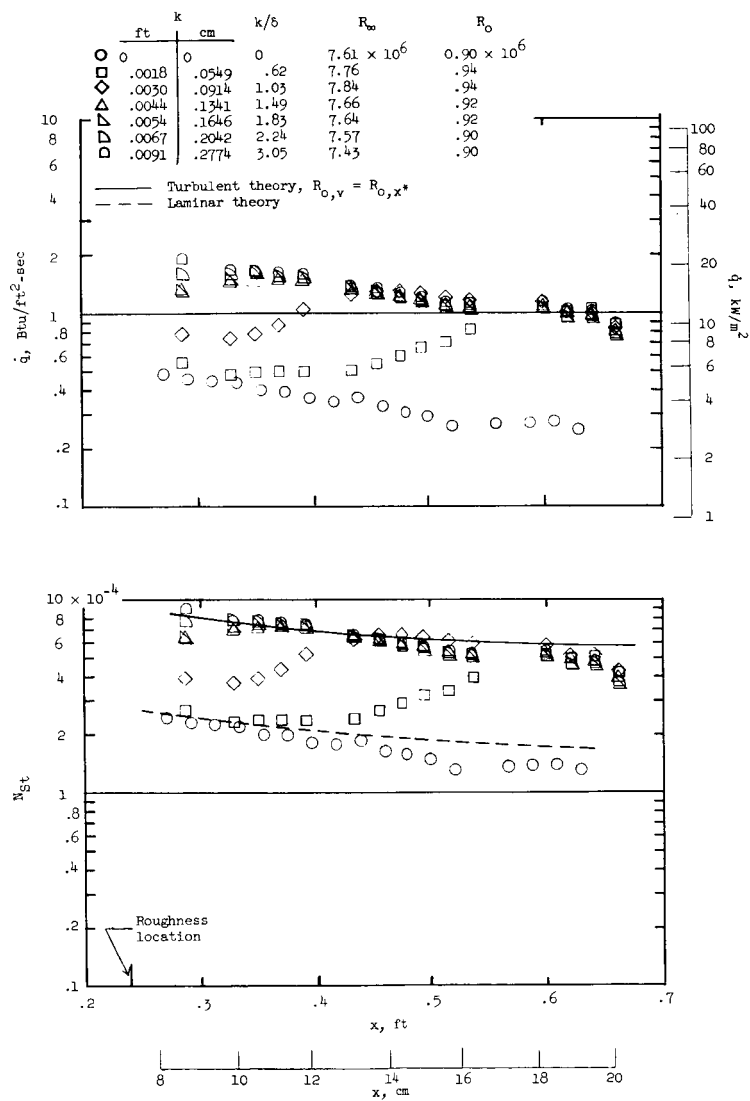


Figure 3.- Determination of transition location from heating-rate distribution.



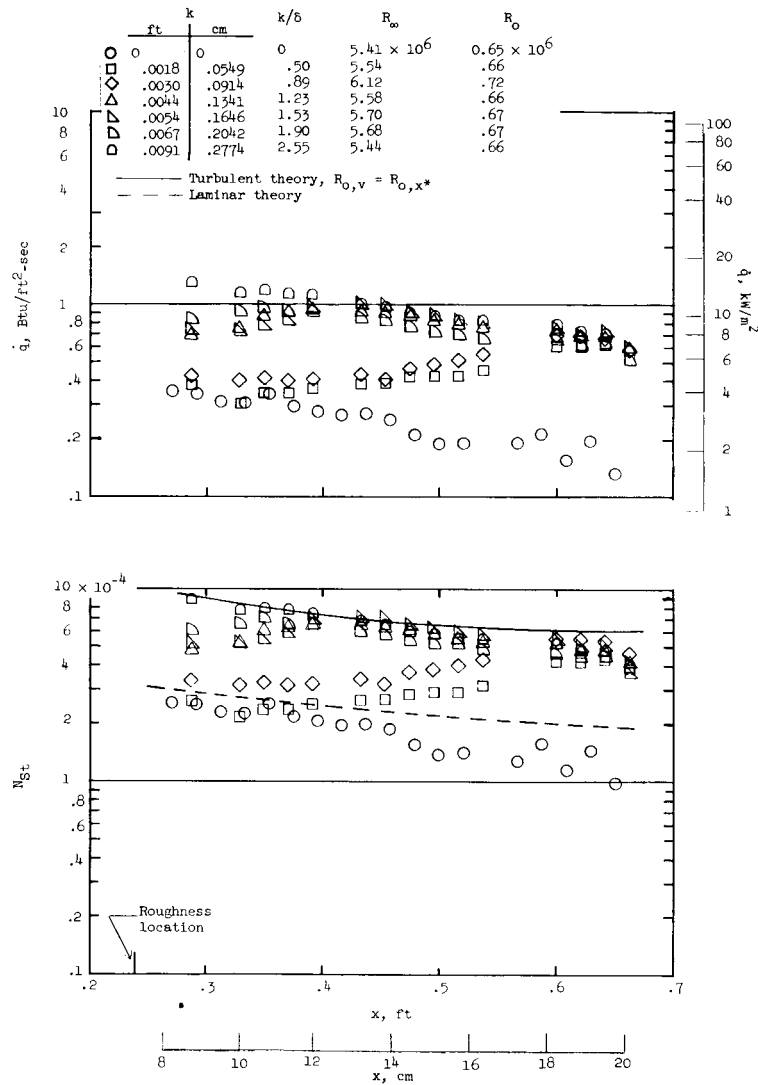
(a) $R_0 \approx 1.10 \times 10^6$.

Figure 4.- Heating-rate distribution on flat plate for various size roughness (spheres). Leading edge A.



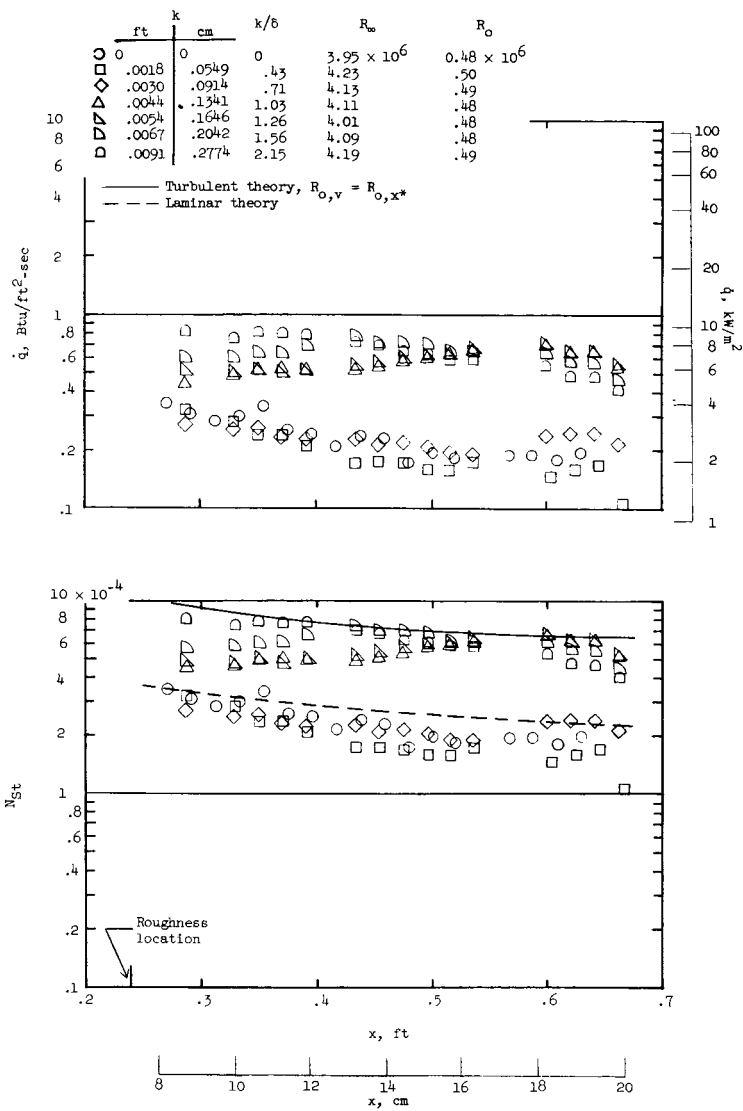
(b) $R_0 \approx 0.92 \times 10^6$.

Figure 4.- Continued.



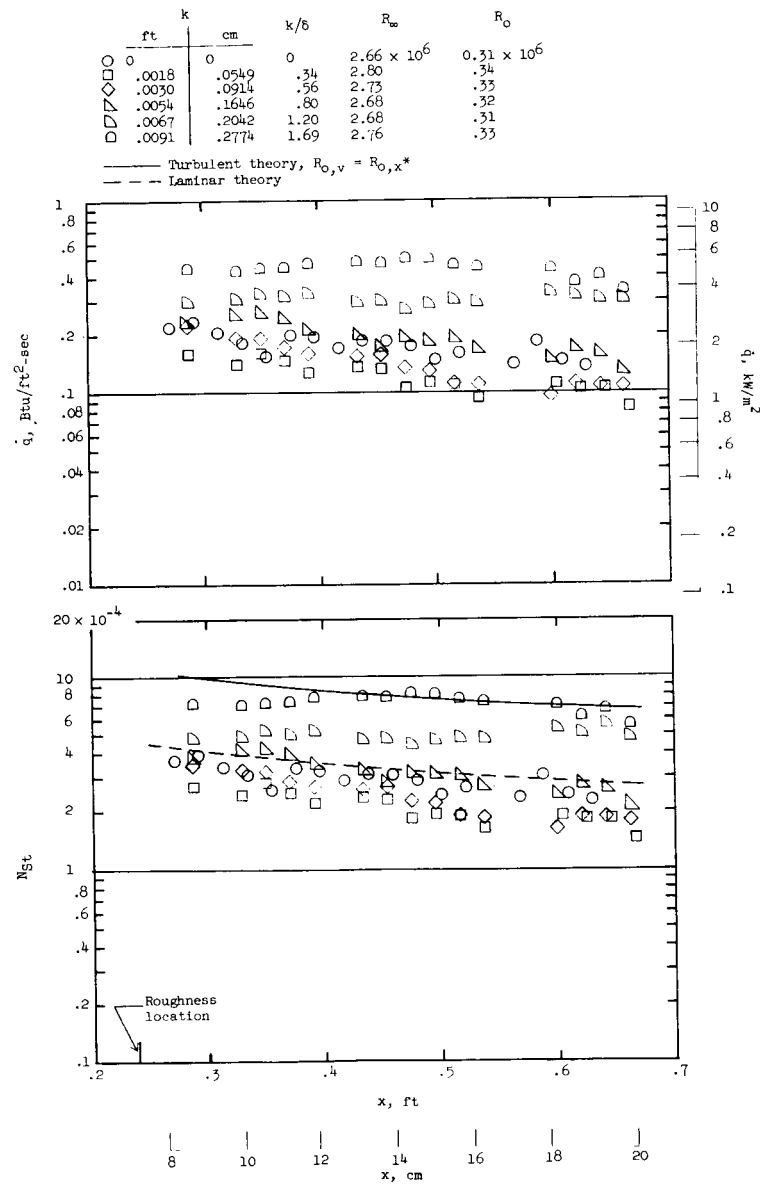
(c) $R_o \approx 0.67 \times 10^6$.

Figure 4.- Continued.



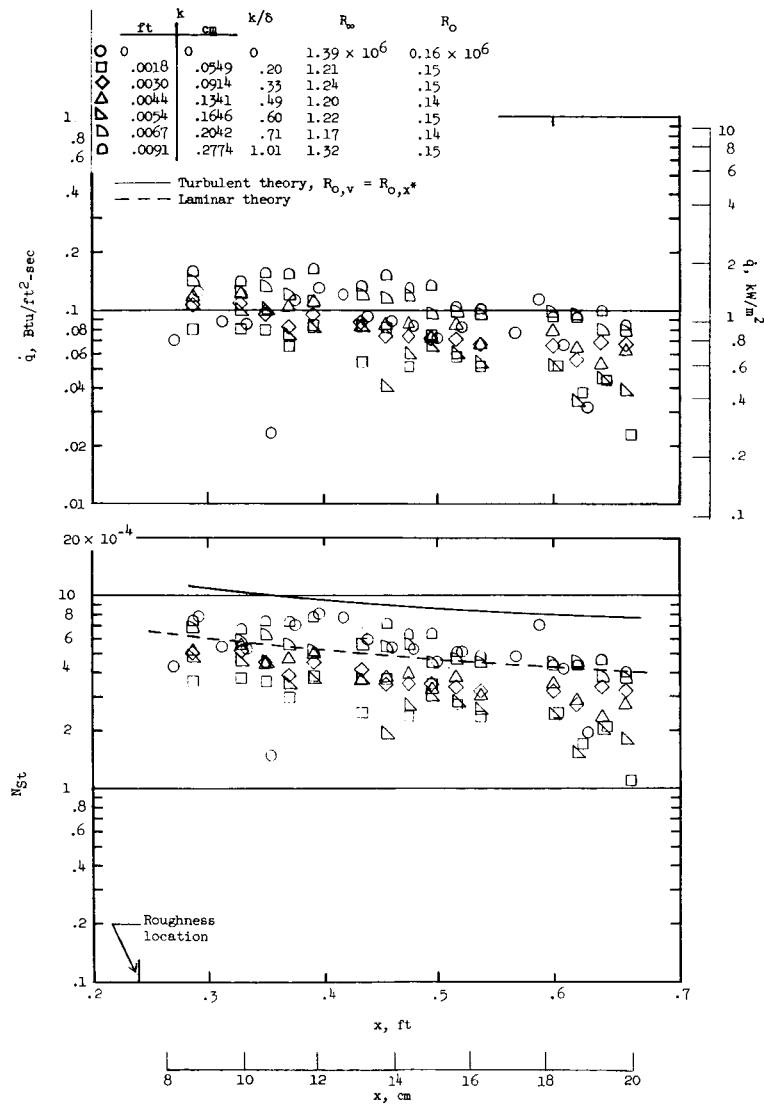
(d) $R_0 \approx 0.49 \times 10^6$.

Figure 4.- Continued.



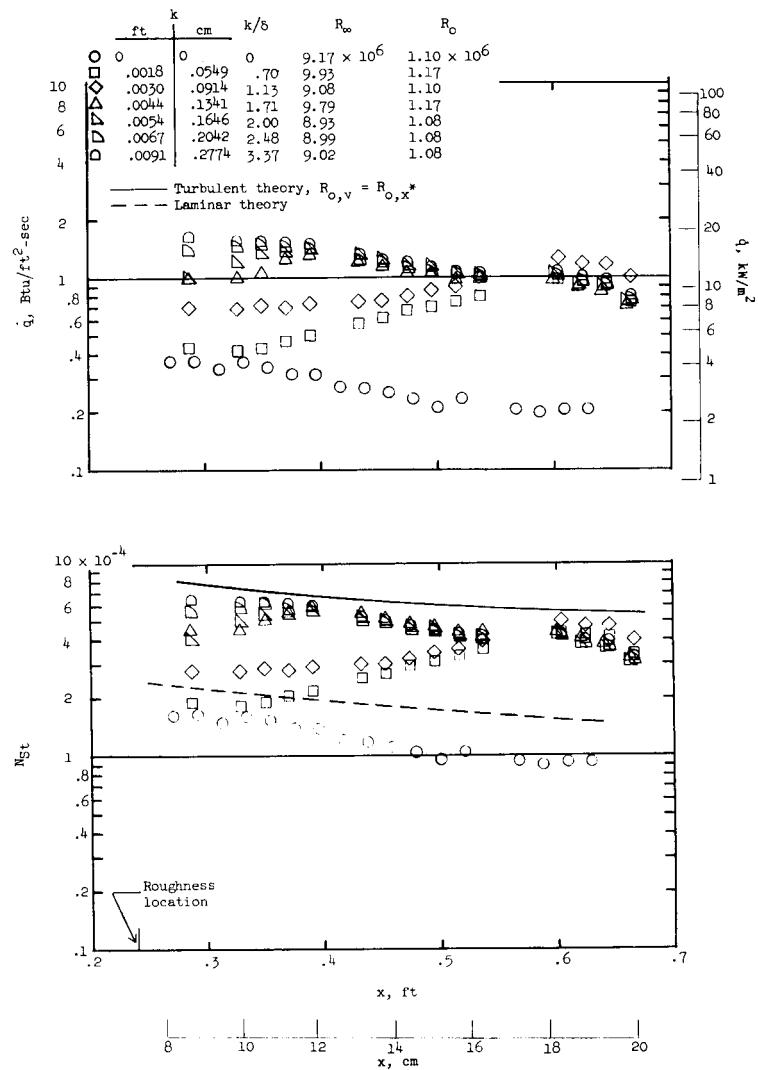
(e) $R_0 \approx 0.33 \times 10^6$.

Figure 4.- Continued.



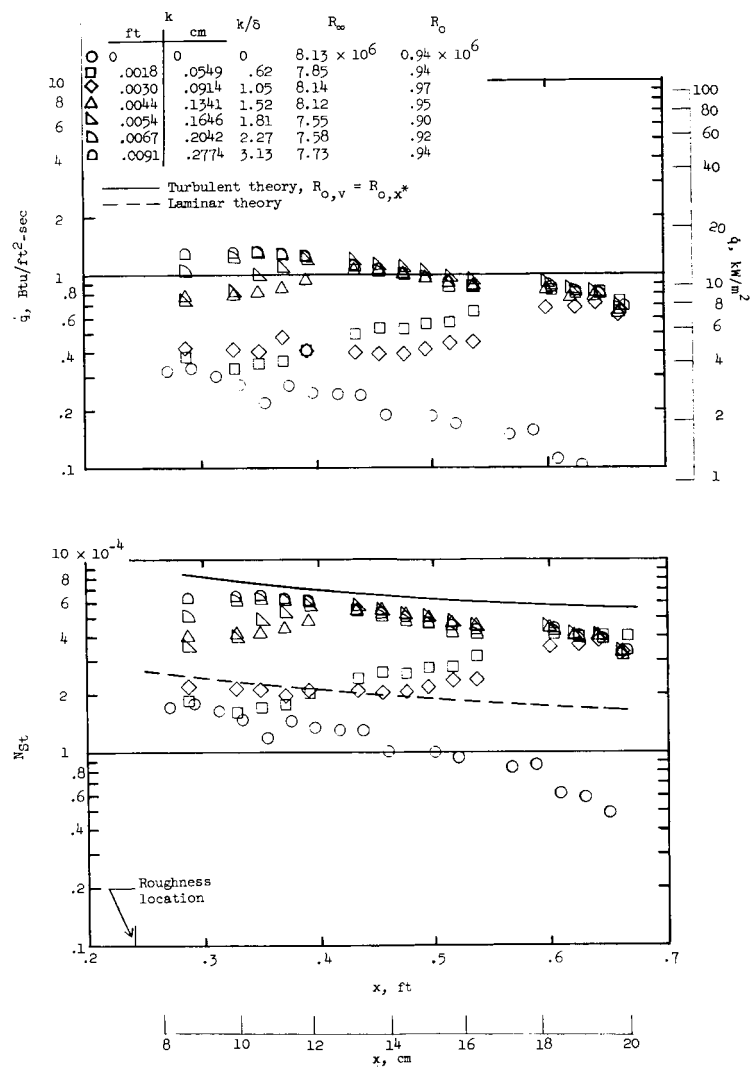
(f) $R_0 \approx 0.15 \times 10^6$.

Figure 4.- Concluded.



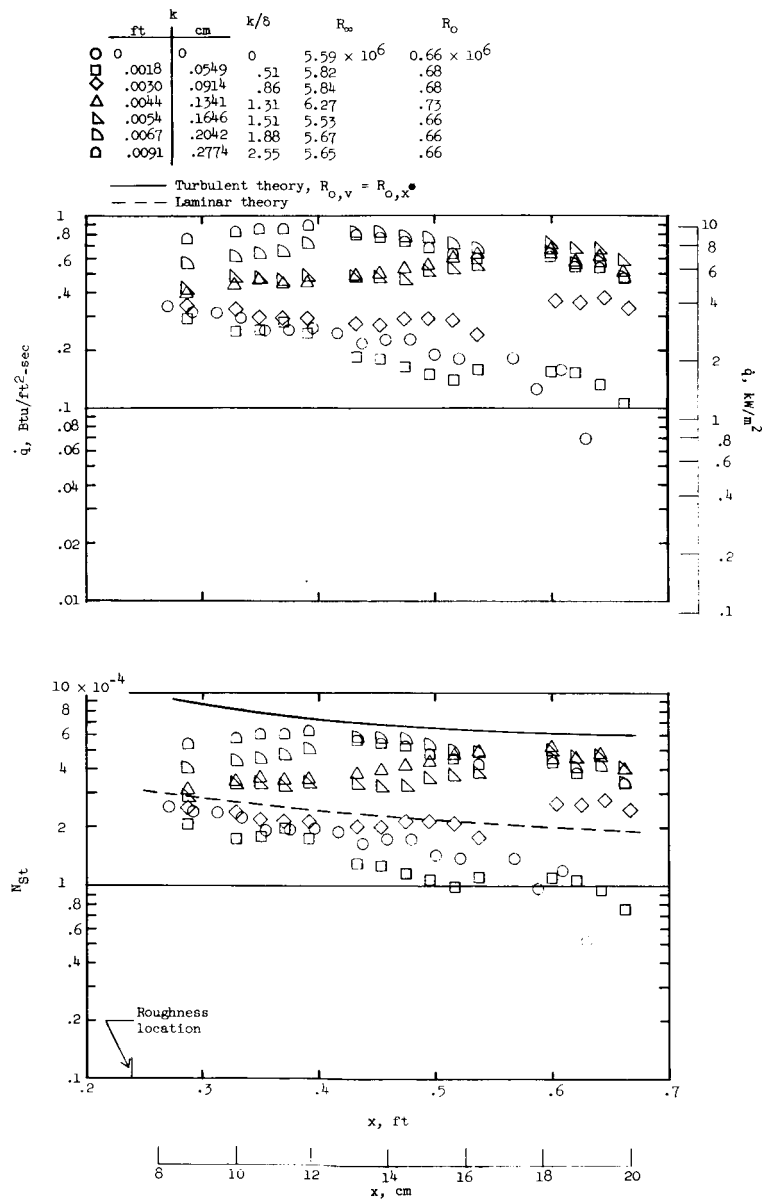
(a) $R_0 \approx 1.10 \times 10^6$.

Figure 5.- Heating-rate distribution on flat plate for various size roughness (spheres). Leading edge B.



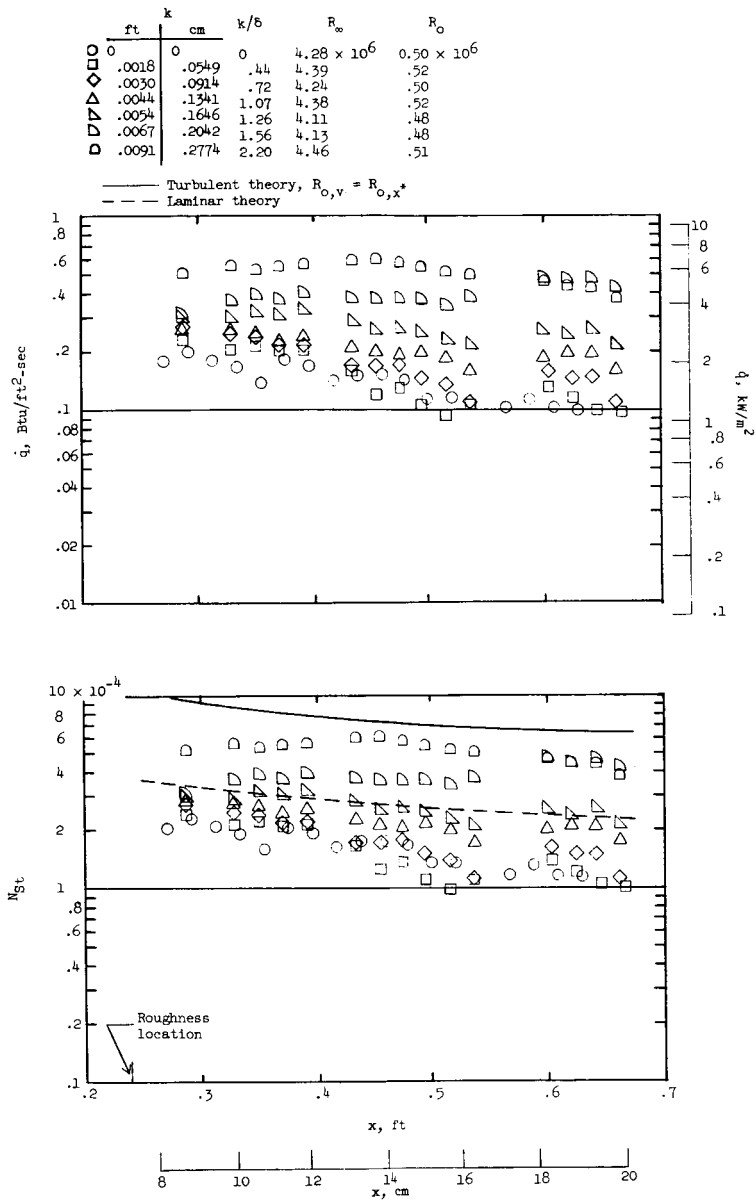
(b) $R_0 \approx 0.94 \times 10^6$.

Figure 5.- Continued.



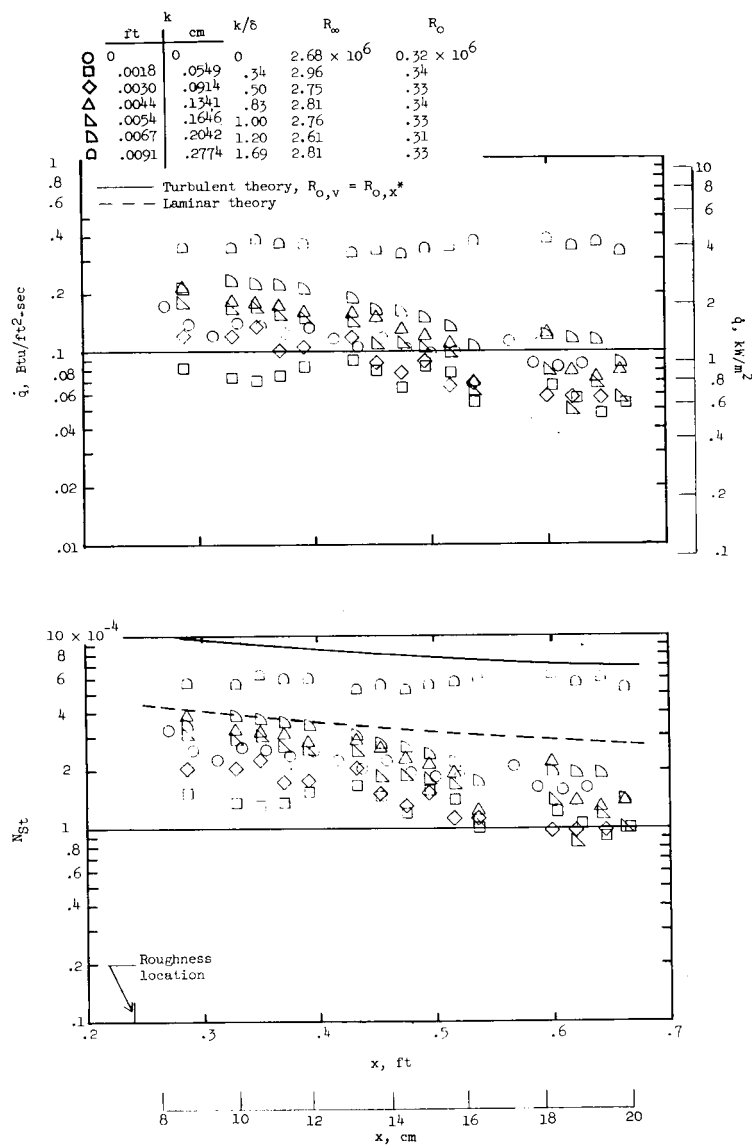
(c) $R_0 \approx 0.68 \times 10^6$.

Figure 5.- Continued.



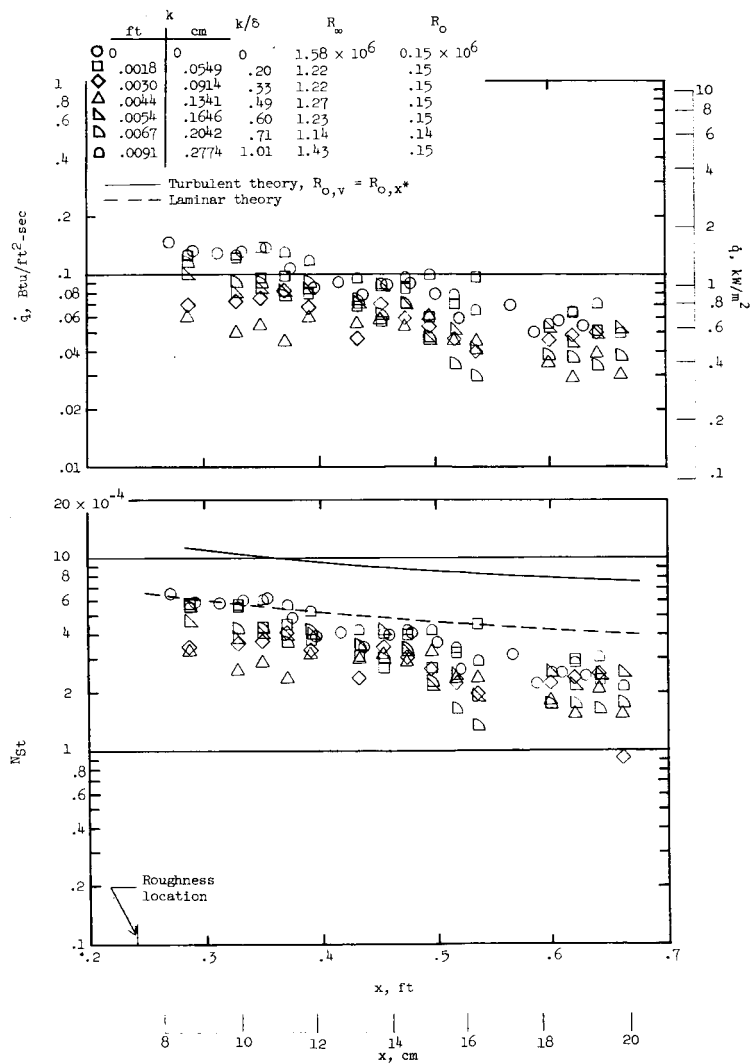
(d) $R_0 \approx 0.50 \times 10^6$.

Figure 5.- Continued.



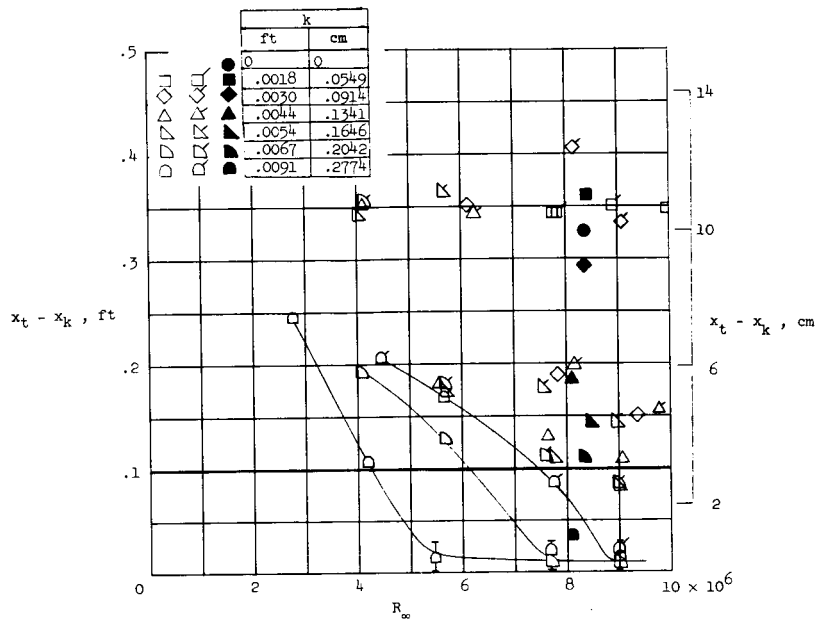
(e) $R_o \approx 0.33 \times 10^6$.

Figure 5.- Continued.

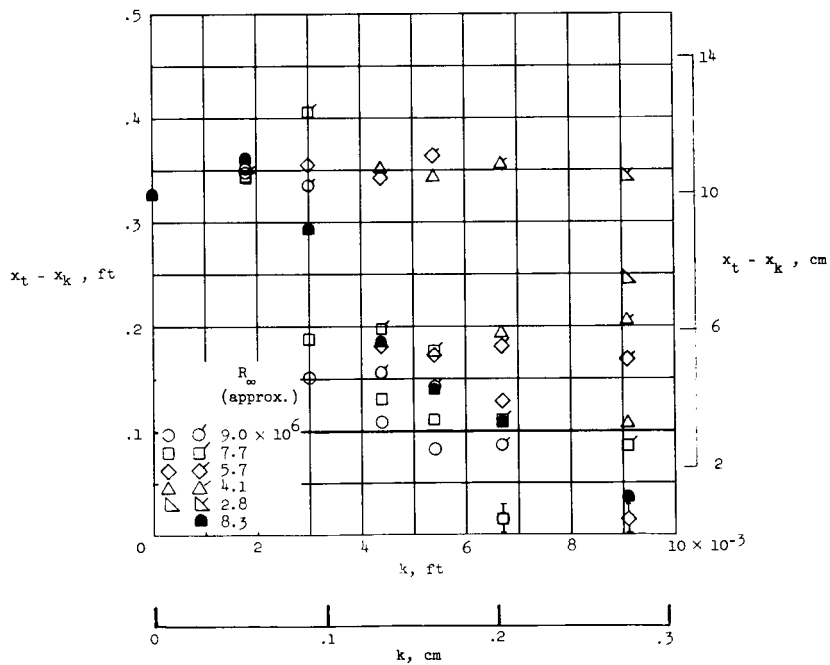


(f) $R_o \approx 0.15 \times 10^6$.

Figure 5.- Concluded.

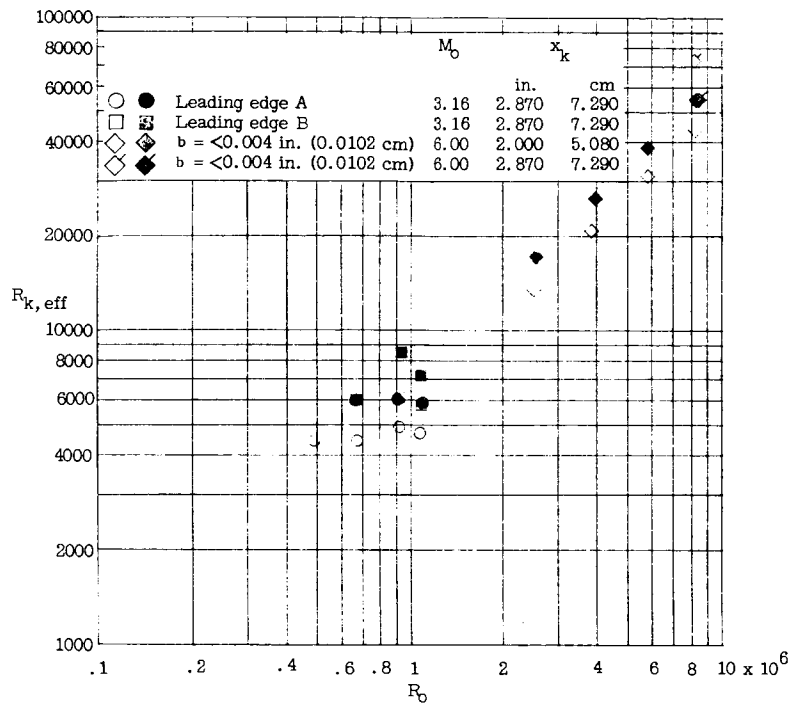


(a) Variation of $x_t - x_k$ with R_∞ for constant values of k .

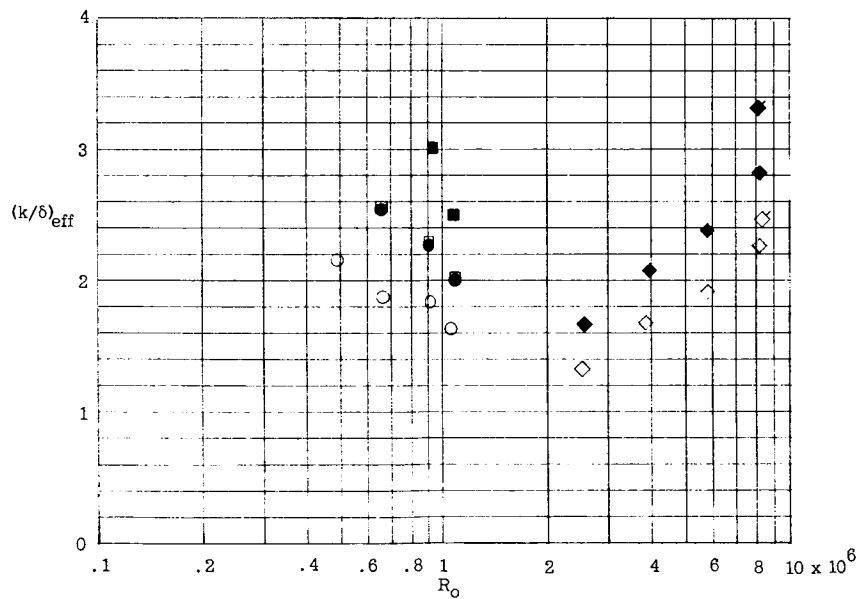


(b) Variation of $x_t - x_k$ with k for constant values of R_∞ .

Figure 6.- Variation of transition location with R_∞ and k . $M_\infty = 6$; $x_k = 2.870$ inches (7.290 cm). (Open symbols denote leading edge A; flagged symbols denote leading edge B; closed symbols denote sharp-leading-edge data of ref. 1.)

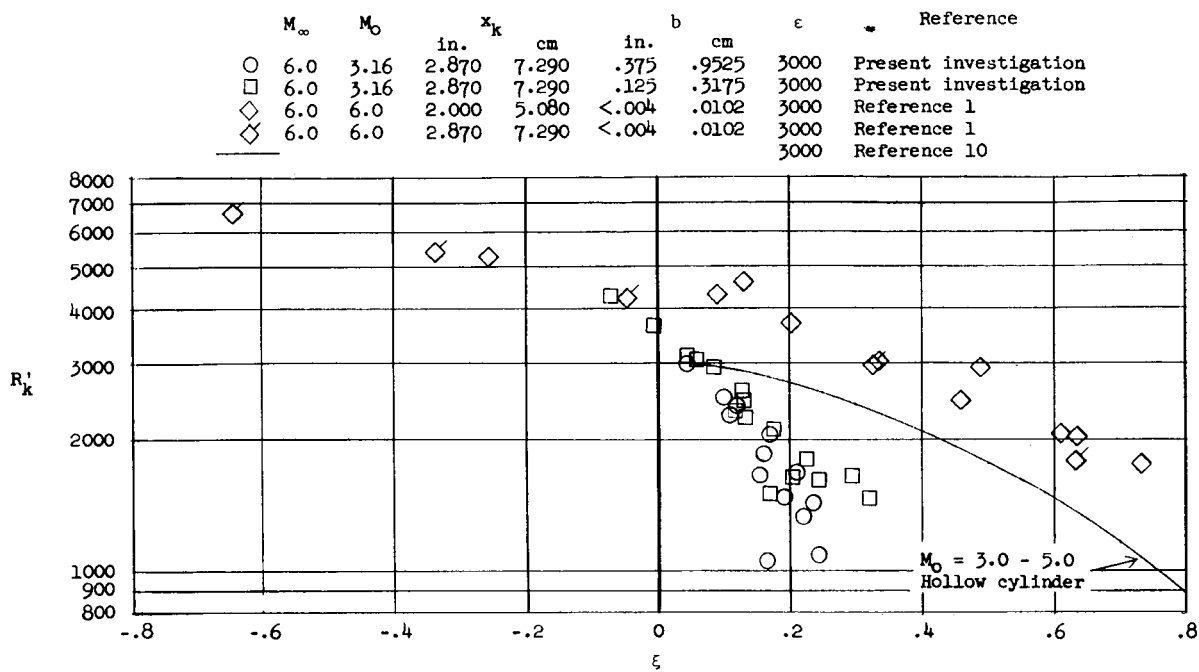


(a) Variation of $R_{k,eff}$ with R_0 .

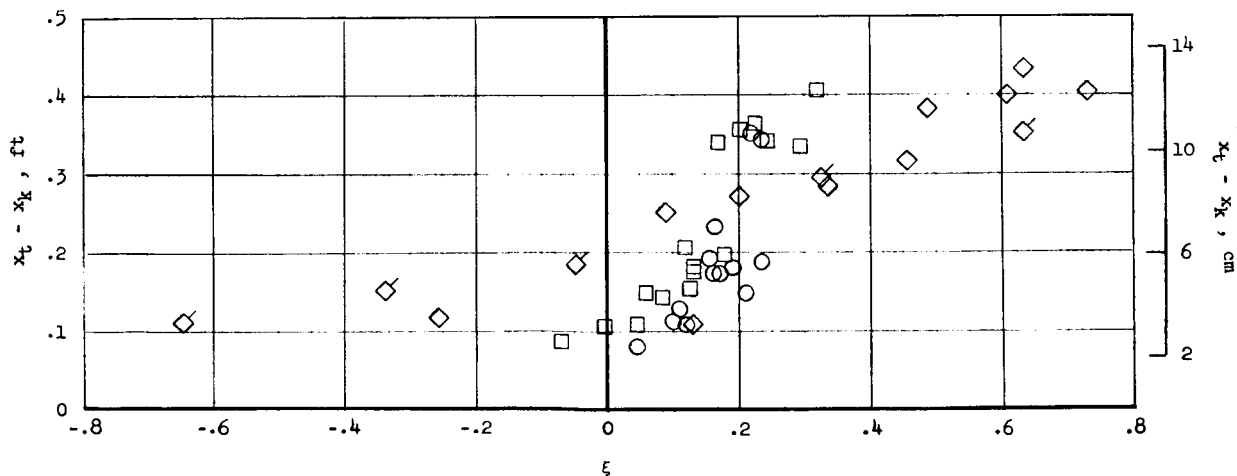


(b) Variation of $(k/\delta)_{eff}$ with R_0 .

Figure 7.- Variation of effective roughness Reynolds number and $(k/\delta)_{eff}$ with local unit Reynolds number. $M_\infty = 6$. (Open symbols indicate roughness height less than the effective value; closed symbols indicate roughness height greater than the effective value.)



(a) Variation of R'_k with correlation parameter.



(b) Variation of transition location with correlation parameter.

Figure 8.- Correlation of roughness-induced-transition data by method of reference 10. $\epsilon = 3000$.

	M_∞	M_0	x_k		b		ϵ	Reference
			in.	cm	in.	cm		
○	6.0	3.16	2.870	7.290	.375	.9525	5500	Present investigation
□	6.0	3.16	2.870	7.290	.125	.3175	5500	Present investigation
◇	6.0	6.0	2.000	5.080	<.004	.0102	5500	Reference 1
◇	6.0	6.0	2.870	7.290	<.004	.0102	5500	Reference 1
							3000	Reference 10

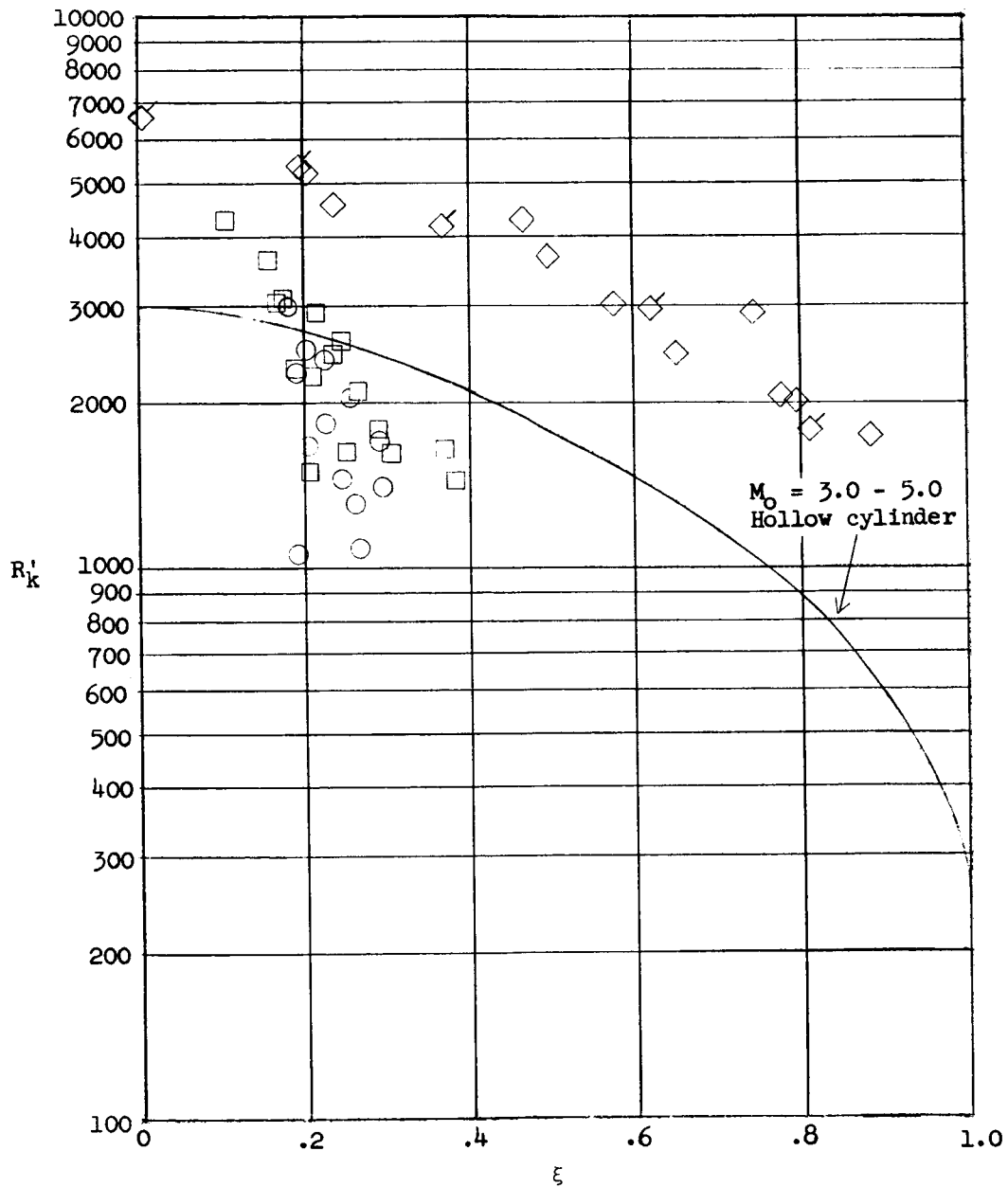


Figure 9.- Correlation of roughness-induced-transition data by method of reference 10. $\epsilon = 5500$.

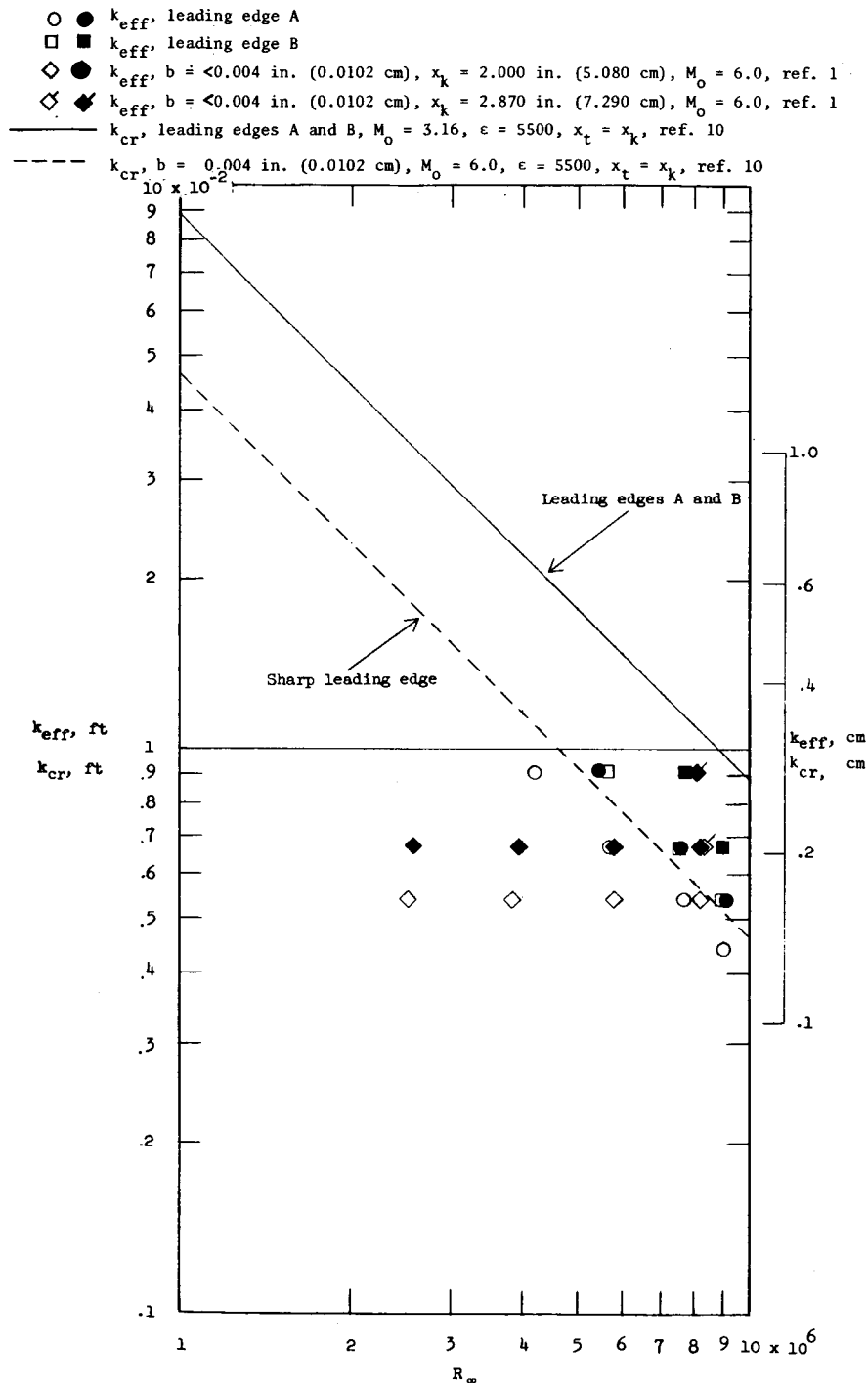


Figure 10.- Effective and critical roughness sizes as a function of free-stream Reynolds number. $M_\infty = 6$. (Open symbols indicate roughness size slightly less than the effective value; closed symbols indicate roughness size slightly greater than the effective value.)